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J. A. Oberdorfer
Dept. of Geology
San Jose State University

R. W. Buddemeier
Lawrence Livermore National Laboratory

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J. A. Oberdorfer
Department of Geology
San Jose State University
San Jose, CA 95192*

R. W. Buddemeier
Nuclear Chemistry Division
Lawrence Livermore National Laboratory
Livermore, CA 94550*

*Work performed at the Australian Institute of Marine Science, Townsville, Queensland, Australia

Abstract

Water movement through the framework of Davies Reef, a coral reef in the central Australian Great Barrier Reef, was studied using field and laboratory determinations of permeability, tide gauge measurements of water levels, dye tracers, and pore water chemistry. Flow is driven by current, wind-induced, or tide-induced water level differences which were shown to occur between reef front and lagoon. The reef is hydraulically very heterogeneous with bulk flow occurring through high permeability zones (voids and rubble) at a velocity on the order of 10 m/d. Pore water exchange in less permeable zones occurs at a much slower rate. Vertical components of flow are significant. Chemical data indicate that carbonate precipitation and solution occur so that porosities, permeabilities, and flow paths may change with time. Implications for nutrient transfer through the benthic sediments and for fresh water resources on reef islands are discussed.

Introduction

Coral reefs are frequently thought of as static barriers to flow in a sea of moving water. In reality, they are hydraulically dynamic systems with water flowing into, through, and out of them continuously, although at a rate much slower than that of cross-reef flow. Knowledge of water fluxes through a reef are important to the understanding of reef diagenesis, as the pore water geochemical transformation that takes place will, in part, be dependent on rate of water through-flow. Nutrient fluxes into and out of the benthic boundary layer will be affected by flow through it. Extension of our knowledge of water movement within a reef to fresh water occurrence in reef islands can increase our understanding of this important resource.

There have been few studies of internal water movement within the structure of a submerged reef. Parnell (1986) used dye tracers to study transport between boreholes in a North Queensland fringing reef; dye arrival times indicated velocities of tens of meters/day. Studies have been performed on water budgets within reef and atoll islands, but these have been limited almost exclusively to the fresh water without examining movement in the underlying salt water (Ayers et al., 1984; Hunt, 1979; Hunt and Peterson, 1980; Lloyd et al., 1980). Often the assumption is made that no flow takes place in the reef salt water. Recent studies of atoll islands (Buddemeier and Holladay, 1977; Buddemeier, 1981; Wheatcraft and Buddemeier, 1981; Herman et al., 1986) indicate the presence of a dual aquifer system consisting of an upper Holocene aquifer of unconsolidated coral sand and rubble (hydraulic conductivity approximately 70 m/d), and a lower consolidated Pleistocene aquifer. Hydraulic conductivities in this lower aquifer are at least an order of magnitude greater and are thought to consist mainly of large void permeability (Ladd and Schlanger, 1960). Data from Kwajalein Atoll (Hunt and Peterson, 1980) indicate the existence of a broad transition zone of mixed fresh and salt water and the probability of significant vertical flow. Computer simulation (Herman et al., 1986) of the layered aquifer system succeeded in matching field data and confirmed the importance of vertical flow.

Pore water velocities can be measured directly using dye tracers or can be calculated from hydraulic data using Darcy's Law, which governs flow through porous media:

$$V_p = \frac{K}{n} dh/dl$$

where V_p is the pore velocity (LT^{-1}), n is the effective porosity (that portion of the porosity where flow actively occurs - dimensionless), K is the hydraulic conductivity of the porous medium and fluid (LT^{-1}), dh is the difference in hydraulic head (L), and dl is the distance between head measurement locations (L).

Reef dimensions divided by the pore velocities will give bulk residence times for water within the reef. Residence times can also be inferred from chemical data, particularly input of a substance which is consumed and depleted, such as dissolved oxygen.

Cross-reef water level differences are thought to be the primary driving force for internal reef flow. These head differences may be created by tidal ponding within portions of the reef or lagoon where outflow or circulation is restricted, or by wind or current induced wave set-up onto the reef.

Evidence from atolls indicates ponding of water within the lagoon in that type of environment, but no such conclusion could be drawn for Davies Reef. Passage of waves across the reef flat may pump water into and out of the uppermost sediments, but is probably not significant to large-scale through reef transport.

Because of the heterogeneity of a coral reef, water will flow at different rates through different components of the reef matrix. Calculations or measurements will usually reflect only a portion of the internal flow environment. Most of the observations and calculations made in this paper refer to that portion of the water moving at high rates through zones of high permeability, in turn reflecting short residence times.

Materials and Methods

Figure 1

This project was carried out on Davies Reef (Figure 1), a coral reef in the central portion of the Australian Great Barrier Reef. The reef is generally covered by 1 to 3 m of water, depending upon tidal stage. It is located about 75 km offshore from Townsville and about 35 km back from the ocean front of the reef system. In May 1982, a 39 m deep hole (AIMS Davies Reef No. 1) was drilled and continuously cored on Davies Reef by the Australian Institute of Marine Science. Samples from this core indicate a solution unconformity at 25.7 m below reef surface demarking the boundary between Holocene and Pleistocene sediments. Sediments both above and below the unconformity consist of dense coral, well cemented sediments, and coral sands and gravel. Sediments in the zone below the unconformity show significant alteration of aragonite to calcite. Davies Reef is probably representative of most mid or back reefs of the Great Barrier Reef system where, in a lower energy environment, reef structures consist of a larger proportion of unconsolidated sediments than is found in more highly consolidated frontal reefs (D. Hopley and P. J. Davies, personal communication, 1985). The reef flat where most of the studies were carried out is covered by reef plate, 0.5 to 1.5 meters thick. This reef plate consists of a highly cemented, algal bound coral gravel.

In January-February 1983, seventeen shallow holes (0.4 to 5.3 m deep) were drilled and cased with PVC casing (Oberdorfer and Buddemeier, 1983). This casing was fitted with an end cap and sampling tube to ensure sampling of formation water as opposed to wellbore water. Three pairs of wells were installed in a cross-reef transect, and the other eleven as a radial array designed for study of horizontal tracer transport
Figure 2 in the subsurface. Figure 2 presents well locations and
Figure 3 depths of the transect wells, and Figure 3 is a diagram of the well casing plus sampling head.

Hydraulic conductivity determinations were made on nine representative core samples using laboratory permeameters. A permeameter consists of a column into which a core sample is sealed. A water level difference applied across the sample induces flow through it at a rate proportional to its hydraulic conductivity. In addition to the core samples from the deep hole, permeameter determinations were also made on two hand samples of the reef plate and on two samples of sand found in pockets on the reef plate. Constant head permeameters were used on the high permeability samples and falling head permeameters on the low permeability ones (Freeze and Cherry, 1979). Constant head permeameters maintain a constant head difference across the sample by adding water to produce a constant discharge. A falling head permeameter is used where the discharge rate is very low and consists of a column to which water is added only once. The rate at which the water level difference decreases is a function of its hydraulic conductivity. The unconsolidated sediments were somewhat disturbed during coring and their emplacement in the permeameter, and may therefore not reflect the exact <u>in-situ</u> hydraulic conductivity.

Slug tests were performed in the field on six of the array wells to determine the <u>in-situ</u> hydraulic conductivity and to quantify the magnitude of lateral heterogeneities. A length of PVC pipe was attached to the top of the existing well casing to extend the casing approximately 1.5 meters above the ocean water level. The sampling tubing was removed from the wells, but the sampling end cap was left intact. The extended casing was rapidly filled with water, and then the drop in water level in the casing was measured as a function of time. The rate at which the water flows out into the formation is proportional to the formation's hydraulic conductivity, which was calculated according to Hvorslev (1951). The casing and end cap were calibrated in a beach sand formation of known hydraulic conductivity.

Horizontal tracer tests were performed on the array wells and vertical tracer tests on pairs of the transect wells in an effort to directly measure pore velocities and flow directions. Fluorescent dye was injected, followed by both visual and instrumented observations. Fluorescein and Rhodamine-B were used in concentrations of approximately 40,000 mg/l. The injection of five liters of dye was usually followed by injection of at least 5 liters of seawater to distribute the tracer into the formation surrounding the well. Visual observations were carried out by snorkelers. Samples for instrumental analysis were collected periodically over a 50 hour period from the sampling tubes in nearby observation wells with a peristaltic pump and were measured with a Turner Model 430 spectro-fluorimeter.

In order to investigate vertical flow patterns, Fluorescein was injected into one well of each of the pairs of transect wells, each of which was completed at a different depth, and the other well was sampled. The injection wells and the other well of each pair was sampled periodically over a 26 hour period.

Prior to these tracer studies, pore water was sampled with a peristaltic pump from the sampling tubes in the transect wells and analyzed for a variety of constituents; all waters were essentially anaerobic, with significant concentrations of

H_2S and NH_3 (Buddemeier et al., 1983). Of interest to this discussion were the alkalinity results which were determined by the method of Smith and Kinsey (1978). Dissolved oxygen was also measured using an oxygen electrode inserted into a chamber in the sampling tube ahead of the peristaltic pump. Seawater over the reef flat was manually sampled for comparison at reference location MT (see Figure 2).

Four submersible tide gauges (measurement frequency: 7.5 min) were installed (see Figure 2) to measure relative water level differences over various parts of the reef. These were gauges with strip chart recorders and were emplaced in January 1983 and retrieved in late March 1983. It was not possible to survey in the tide gauges, so that only relative differences in water levels can be deduced. Two current meters were also deployed; their results will not be discussed in this paper.

Results

Permeametry on deep well cores and hand samples indicate large vertical inhomogeneities in the reef's hydraulic properties. Hydraulic conductivities (K) determined by
Figure 4
permeameter are given in Figure 4. Values vary over four orders of magnitude and range from fairly high to fairly low permeabilities relative to the total range generally observed for sedimentary materials. The greatest permeabilities in reef structures most likely result from large voids which are not sampled by coring nor appropriate for permeameter studies, and so are not represented in these results. The reef plate

has a hydraulic conductivity several orders of magnitude less than that of the underlying sediment and probably acts as a confining layer. This layer restricts flow through the reef flat surface and may create pressurized conditions within the reef. It is, at least locally, a leaky confining layer (as was made apparent in several of the dye studies where dye leaked through the reef plate), in that fissures or small holes in the reef plate can allow the passage of water at a much greater rate than through intact reef plate itself. These results are consistent with the observations of Ayers et al. (1984) in the Caroline Islands.

Figure 5

The results of the slug tests are given in Figure 5. One advantage of slug tests over permeameter determinations of hydraulic conductivities is that they give a value integrated over a much larger volume of porous medium and thus give values more representative of formation permeability. The data show that order of magnitude changes in hydraulic conductivity occur over lateral distances of 10 m, so there is horizontal, as well as vertical, inhomogeneity. There is good agreement between the values of hydraulic conductivity found for the upper 3-4 m of the AIMS Davies Reef No. 1 Core and the values found for the shallow array wells.

Head differences (measured as water level difference) results can only be analyzed in relative terms since there was no common datum for the tide gauges. The tidal curves from the different gauges can be matched in a variety of manners,

Figure 6

Figure 6 being an example of one of them. What is clear is that the curves from the reef front and from the lagoon do not match for the whole tidal cycle. For some period of time, the water on one side of the reef flat is several centimeters to several tens of centimeters higher than on the other side. This would create a sufficient gradient to induce significant flow through the reef.

Calculations can be made using Darcy's Law if we make several assumptions:

1. High permeability zones ($K \geq 1000$ m/d) dominate the internal flow;
2. Void porosity (that portion of the total reef volume where high rate flow is taking place) is approximately 5%; and
3. An average head difference across the 300 m width of the reef is 5 cm.

$$v_p = \frac{1000\ \text{m/d}}{0.05}\,\frac{0.05\ \text{m}}{300\ \text{m}} = 3.2\ \text{m/d}$$

A range of probable values would be plus or minus one order of magnitude. This calculated pore velocity value would give a residence time (or travel time across the 300 m width) of approximately 0.25 year. This is generally consistent with the through-reef flow rates estimated by Buddemeier (1981) for the larger Enewetak atoll reef system.

If vertical flow caused by tidally induced pressure-head variations in a highly permeable Pleistocene aquifer predominates, the distance over which that head difference exists is < 300 but $\geq$ 25 m, and the minimum travel distance becomes approximately 25 m. In turn, the maximum vertical pore velocity calculated is 10 m/d, and the minimum residence time is 2.5 days.

The horizontal tracer test on the array wells was conducted over a period limited to two days by the ship's schedule. During this period, no dye was detected in the water samples from the monitoring wells after injection of the central well. This may be because: a) the dye had not had time to reach the monitoring wells over the two day sampling period, suggesting flow velocities less than 5 m/d; b) the monitoring wells were emplaced at points in the highly heterogeneous formation which did not intercept the major flow channels; or c) the dye had been diluted below detection limits before arrival. Visual observations were made, however, as dye injected into the wells emerged at the reef surface through fissures in the reef plate. Pore velocities for the visual observations were calculated using the distance from injection to observation point and the time from injection to first observation. A first, strictly visual test using Fluorescein in the central array well in January 1983 indicated velocities of 400-500 m/d in a direction diagonally toward the reef front (toward Array Well 3). These velocities would yield residence times of less than one day. Dye from this first injection was found in Well 7 when it was first sampled 42 days later. This would indicate velocities greater than 0.2 m/d. This Fluorescein concentration of 14-20 ppm persisted during the March 10-12 sampling period. A second Fluorescein injection in the central array well on March 10 produced no visible leaks.

The March 12 Rhodamine-B injection into Array Well No. 1 produced surface leaks from a coral head 0.6 m to the north after one half hour; after two and one half hours, dye was streaming from 10 to 15 locations around the well. Velocities of 20 to 50 m/d, primarily in the vertical direction, were calculated from these observations. Similar visual tests attempted on Wells 6, 8, and 10 produced no observable leakage.

In the vertical dye experiments on the transect wells, no dye was observed in Well FS after injection into FD. Well MS had dye concentrations of 0.03 ppm and 0.05 ppm at 23 and 26 hours after initial injection into MD. From the MS data, an upward vertical velocity of less than 5, but greater than 1.4

Figure 7 m/d, can be estimated. Figure 7 gives the results from Well BD. The results for BD suggest that both upward and downward movement may be taking place, upward on the rising tide and downward on the falling tide, although not enough data were collected to verify this. The arrival in the downward direction after three hours suggests a vertical velocity of about 12 m/d, consistent with the estimate calculated above. Although transport times are similar, much higher concentrations were advected downward from BS to BD than were moved upward from MD to MS.

Small (but significant) variations in the very low levels of dissolved oxygen on the order of 0.10 to 0.20 ppm were observed in a number of shallow wells, which indicated input of oxygen-bearing seawater on a tidal cycle basis. These concentrations reflect an exchange of about 3% ocean water with the pore water over each tidal cycle. This replacement rate would indicate a pore water residence time of approximately 17 days. Since oxygen is not a conservative tracer in this environment, the actual residence time at shallow depths might be significantly less. Pore water sampled for chemical analyses may well be a mixture of rapidly moving pore water plus more stagnant water, so the chemistry may reflect multiple residence times. Oxygen response was fairly rapid in the wells, indicating pore water velocities on the order of 10 m/d. Since oxygen is consumed very quickly within the reef structure, the most likely input would be by the shortest flow path, which is downward movement from the seawater overlying the reef flat (in other words, by a predominantly vertical pathway).

Table 1

Table 1 summarizes the pore water velocity and residence time results. Somewhat different results are obtained from calculations based on primarily vertical, as opposed to

Table 2

horizontal, flow. Alkalinity data (Table 2) from the wells and the overlying seawater indicate that both solution and precipitation of carbonate minerals are taking place once the seawater enters the reef structure; a decrease in pore water alkalinity relative to seawater indicates net precipitation, while an increase indicates that net solution is taking place. These solution and precipitation processes will alter the porosity and, hence, the permeability of the formations with time. Buddemeier et al. (1983) have presented a preliminary report on the pore water geochemistry; a more extensive paper by the same authors is in preparation. Sansone (1985) has reported additional data in the context of a different investigation using some of the same wells.

Discussion

The work of Parnell (1986) has produced dye tracer measurements of reef pore water movement which have better vertical and horizontal resolution than the results reported here; his study, however, had no measurements of geochemical characteristics or of hydraulic gradients or conductivities. In view of similarities and differences between the studies, a comparison is interesting.

There are three major points of qualitative similarity between the results of the studies: 1) Parnell's velocities are consistent with the upper end of the velocity range observed or calculated in this study; 2) considerable vertical movement occurs, with an apparent preference for downward transport; and 3) some boreholes lost dye more slowly than would be predicted from first-arrival velocities. Inferences common to both studies are that pore water flow is variable in both rate and direction, and that the reef framework is hydrologically heterogeneous and probably more analogous to a fracture-flow than to a porous medium situation in terrestrial hydrology.

The similarities in results are striking in view of differences between the study locations. Parnell's site was a leeward fringing reef which is subaerially exposed for part of the tidal cycle, may have substantial fresh water and terrigenous influence, and in which the Holocene framework overlies a (presumably low permeability) terrigenous Pleistocene substrate. As described above, Davies Reef conforms to none of these descriptions. To the extent that their hydrologic similarities are not coincidental, they must reflect the dominant influence of factors common to both sites. These factors are the characteristics of coral reef sediments (including their depositional, erosional, and diagenetic characteristics), and variations in water level and hydraulic gradient influenced primarily by tidal fluctuations augmented by wind-generated effects.

While the Davies Reef pore water velocity results vary a great deal, they indicate that the most likely values for pore water residence time in the high permeability zones of the upper few meters of the reef structure are in the range of a few weeks to a few months. These values reflect the movement of that portion of the formation water which is actively circulating. Residence times for water entrapped within the coral fragments, dead end pores, or less permeable sediments would be much greater. There is certain to be some degree of exchange between the open and the more restricted flow paths. The relatively short residence time for the mobile water means that large volumes of water are entering and leaving the reef structure on a yearly basis, although this water may flush a rather small fraction of the total reef pore volume because of preferential flow through high permeability pathways. These large fluxes (10-1000 m^3 of water per m^2 of reef surface per year) show the potential for substantial exchange between the nutrient rich reef pore waters and the benthic sediments. The large fluxes also signify that significant portions of the carbonate reef structure can be altered by solution or precipitation, and that biological activity can be sustained within ostensibly remote locations in the reef substructure. At a site where fresh water influences are possible (e.g., Parnell's), increased dissolution may produce higher permeabilities and pore water velocities than found in the strictly marine system.

The dye and the oxygen renewal data suggest that vertical flow is important. We cannot tell whether the mechanism for this involves coupling with a permeable Pleistocene aquifer as in the atoll island case (Herman et al., 1986), or whether it is the result of wave and tide action on the reef surface as suggested by the results of Parnell (1986). In either case, vertical flow has important implications for coral reef geochemistry as it does for fresh groundwater resources on atoll and reef islands.

In the island groundwater case, the vertical motion causes mixing of fresh water with underlying salt water and the establishment of a deep transition zone of brackish water; the

Pleistocene aquifer serves as a conduit for net removal of fresh water and for transport of reduced salinity pore water into reef framework environments far removed from the island surface. The geochemical implications for a marine reef with vertical pore water flow are analogous: surface ocean water freshly introduced into the framework would be mixed with older pore waters to a considerable depth, enhancing the potential for biogeochemical alterations throughout the system.

By way of conclusion, we state that:

1. This study demonstrates that it is possible, although by no means simple, to make direct observations of hydrologic processes occurring within the structure of a coral reef.

2. Davies Reef is heterogeneous, generally permeable, and has relatively rapid and convoluted internal flow patterns. Data on the hydrologic characteristics of this submerged reef are consistent with observations obtained from other reef studies (Parnell, 1986) and island hydrology studies (Herman et al., 1986), suggesting consistency in the controlling parameters for coral reef systems in general.

3. Even in the absence of major barriers and enclosed lagoons, the reef system generates head differences, most likely tide or wind induced, capable of driving a significant internal flow.

4. More detailed future investigations are needed to characterize flow velocities and directions, the rates of nutrient regeneration, and the rates and effects of carbonate dissolution and precipitation.

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Table 1. Pore velocities (V) and residence times (τ) for Davies Reef, determined by various experimental methods

	Horizontal		Vertical	
	V (m/d)	τ(days)	V(m/d)	τ(days)
Calculation (Darcy's Law)	3.2	90	10	3
Dye Tracer	> 0.2	< 1500	>1.4 to <5	>6 to <20
	400	< 1	10	3
			20 to 50	<1 to 2
O_2 Renewal	—	—	10	<17

Table 2. Average pore water alkalinity values and ocean water value at mid-transect (MT)

Well No.	Alkalinity (meq/l)
FD	2.319 ± .013
FS	2.272 ± .014
MD	2.410 ± .011
MS	2.197 ± .007
BD	2.178 ± .002
BS	2.280 ± .005
MT (seawater)	2.346 ± .001

Figure Captions

Figure 1. Location of Davies Reef study area, central Great Barrier Reef.

Figure 2. Detailed map of Davies Reef study area with well locations, transect well depths, and tide gauge and current meter locations.

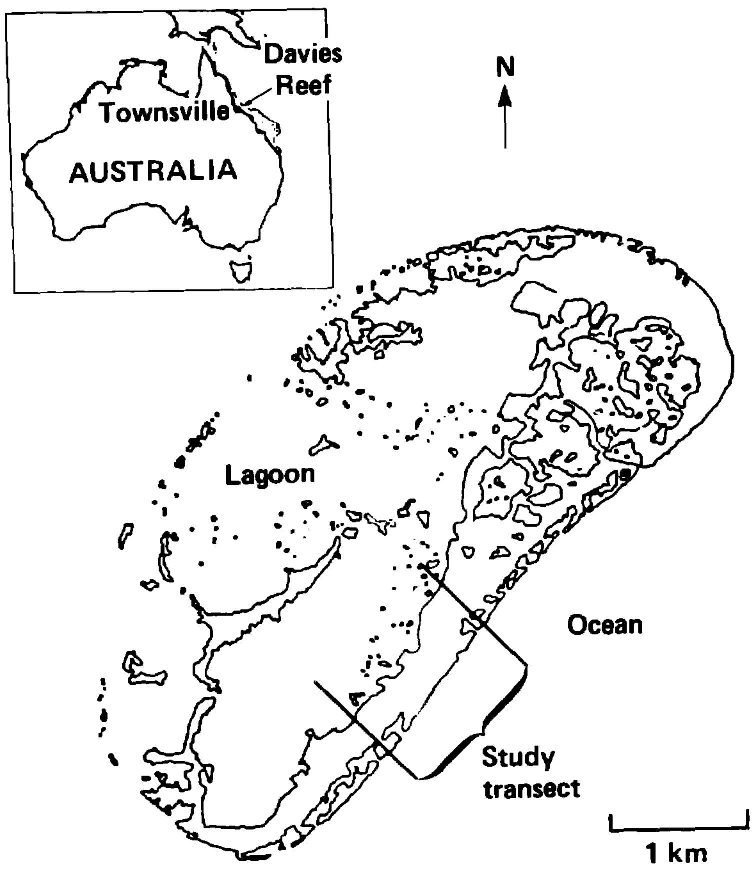
Figure 3. Sampling well schematic.

Figure 4. Hydraulic conductivity results from permeameter studies of Davies Reef No. 1 core, reef plate, and sand on reef plate.

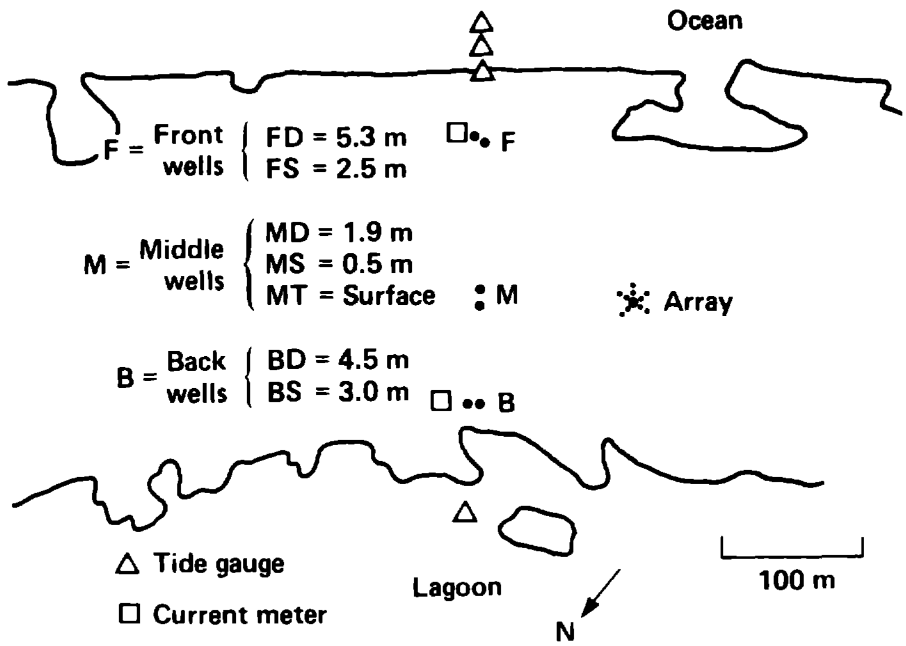
Figure 5. Hydraulic conductivity results (meters/day) from slug tests performed on array wells. Depth of array wells in parentheses.

Figure 6. Tide gauge comparison. Records arbitrarily assigned same level at low tide; absolute differences not known.

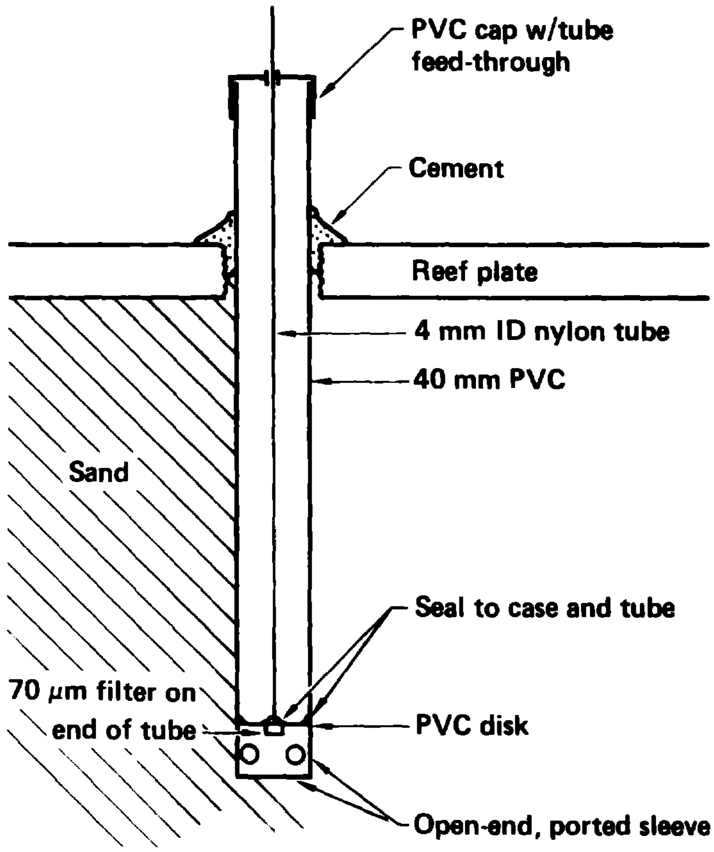
Figure 7. Vertical tracer experiment dye concentrations in well BD. V indicates time of high (H) or low (L) tide.



Oberdorfer & Buddemeier, Fig. 1



Oberdorfer & Buddemeier, Fig 2



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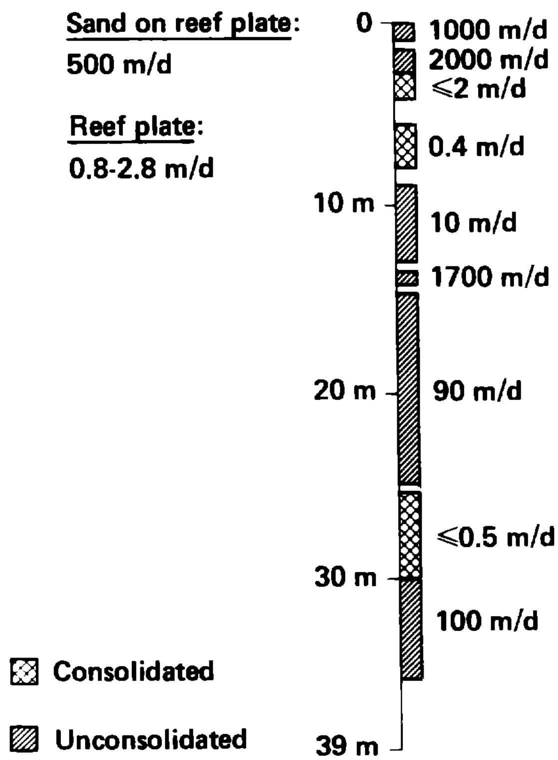

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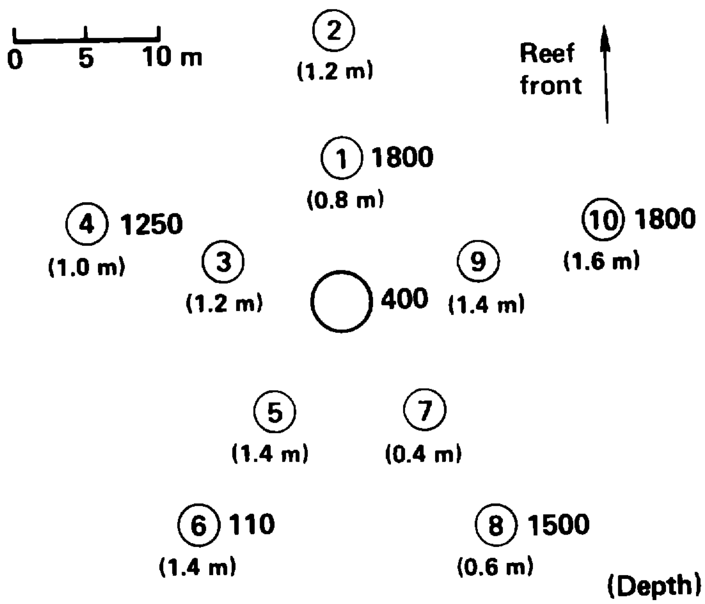

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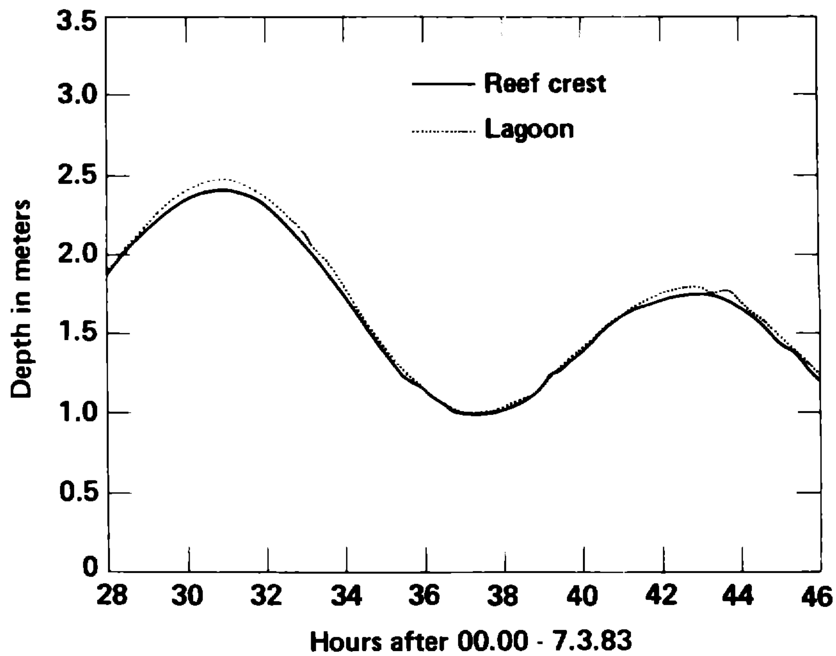

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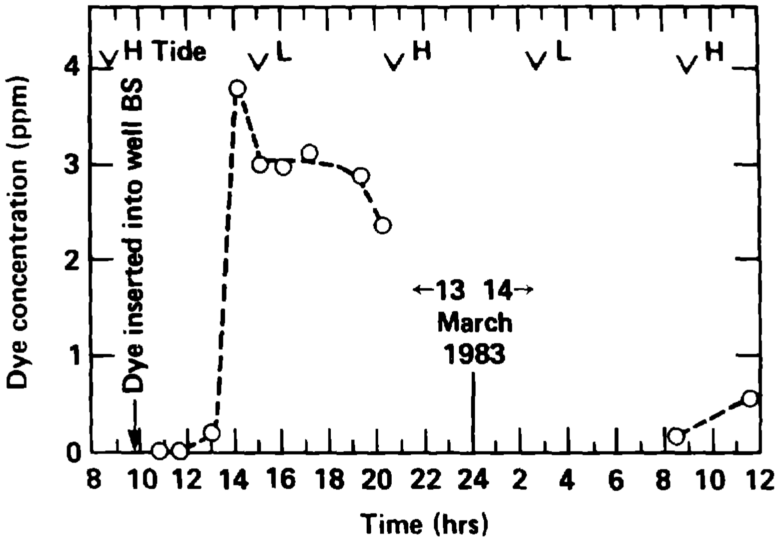

Oberdorfer & Buddemeier, Fig. 7